Minimizing thermal defocus effects in liquid lens based autofocus imaging systems using partial passive optical athermalization (PPOA)

1. Introduction

Today's smart miniature imaging systems would consist of a compact variable focus element, which may be a voice coil motor, liquid lens, or perhaps even an electrically variable liquid crystal lens. While the logic for performing autofocus function is provided by an embedded system controller, the compact variable focus element provides the physical means to focus the image produced by a miniature imaging system. In recent times, liquid lenses have been packaged into compact liquid lens modules (LLMs) that are readily available as off-the-shelf commercial products. As such, they are an appealing solution for customized miniature imaging systems that require variable focus control. LLMs are relatively compact, have fast response times, and have high reliability. However, the focal length of liquid lenses are, to a larger degree compared to glass lenses, susceptible to variations in temperature. As a result, the final image formed by an optical imaging system that includes a liquid lens component may shift in its focal position whenever the temperature of the liquid lens changes. If the temperature is time dependent, then so is the thermal defocus, resulting in possible image blur during the course of image capture at the camera's sensor.

In smart cameras, thermal defocus of the image may be compensated through the use of calibration procedures that take advantage of an embedded system controller that would have been integrated with the imaging system. During factory calibration, measured values of the liquid lens's focal length $f$ versus temperature $T$ at a variety of conditions would be stored as look up tables (LUTs) in a system on module (SoM). Calibrated thermistors may be mounted at appropriate locations inside the LLM to measure temperature. During operation of the imaging system, measured temperatures inside the LLM may be fed back into the SoM, which can then apply an algorithm to determine the appropriate liquid lens's focal length for active defocus compensation in response to changes in temperature. The SoM then communicates with driver electronics to make all of the proper focus adjustments.

But perhaps in some other cases, design constraints may prohibit the inclusion of thermistors into the LLM. In such cases, how would one manage thermal defocus effects? In this white paper, we describe how this may be done through the application of basic imaging principles. In particular, we show that in an arrangement where the LLM is mounted in front of a fixed focus lens (FFL) to provide focus adjustment, thermal defocus of the final image is minimized when the liquid lens's focal length is set to infinity, and the fixed focus lens is set to focus at some distance other than infinity. In this paper, we refer to such a condition as “partial passive optical athermalization” (PPOA).
2. Optical System Design with Liquid Lens for Variable Focus Adjustment

In this section, we begin with a brief overview of how to integrate a LLM with a FFL (i.e., a lens whose position is fixed relative to the image sensor in a camera). Perhaps the most straightforward way to use a LLM as a variable focus element in an imaging system is to mount the LLM in front of a FFL as illustrated in Fig. 1. The principle of operation for such a configuration is that, as the object is shifted between its near and far positions relative to the imaging system, the liquid lens’s front focal length $b$ is made to change accordingly such that light from the object emerges as parallel rays from the liquid lens prior to entering the FFL. The rays from the object are then said to be collimated by the liquid lens. In this way, the FFL’s focus is fixed at infinity and is said to be operating at “infinite conjugates”. The FFL remains at a fixed position and focuses the collimated rays onto the image sensor, which is located at the back focal position of the FFL. The image sensor also remains fixed in its position. In the following section, we shall see that the infinite conjugate arrangement between the LLM and FFL is actually not the ideal optical setup when thermal defocus effects are present.

![Fig. 1 Focusing with a LLM mounted in front of a FFL using infinite conjugate setup for the FFL.](image)

3. Applying the Basics: Partial Passive Optical Athermalization (PPOA)

In theory, it is possible to minimize thermal defocus effects even if no active focal length compensation is performed on the liquid lens. As is explained in the colored panel on partial passive optical athermalization (PPOA), image defocus from thermal effects is reduced whenever the focal length of the liquid lens is large. In fact, note from Eq. 2 that $\frac{db}{df} = 0$ as $f$ approaches infinity, which means that $\frac{db}{dT} = 0$ also in this limit. This suggests that a preferred optical configuration between the LLM and FFL is to set the liquid lens’s focal length to infinity at the object’s nominal working distance. Under this condition, the liquid lens essentially acts as a simple window through which the FFL looks, and the FFL focuses the transmitted light on an image sensor located at a fixed distance behind the FFL. In this way, the object is at the near focus position (Fig. 2a), and a finite negative focal length when it is at the far focus position (Fig. 2c). In this way, the nominal WD may be regarded as the mid-focus object position. At this position, $\frac{db}{dT} = 0$ because $f$ is infinite, so the imaging system becomes essentially invariant to small changes in temperature.

As an illustrative concept design example of an imaging system with PPOA, consider the modelled
imaging systems shown in Figs. 3a and 3b using the Zemax optical design program\(^1\), where a LLM is mounted in front of a simple compact FFL, whose focal length is 10 mm (i.e., $F = 10$ mm in Eq. 2). In the Zemax models, the LLM is modelled as a thin ideal lens (i.e., it is a so-called “paraxial lens model”). As a representative example, we have assumed the use of the Arctic 25H LLM from Varioptic\(^2\). According to the specifications provided at the Varioptic website, this liquid lens’s focal length may be varied from $f = -200$ mm to infinity, and from $f = +77$ mm to infinity. In this concept design, the object’s nominal WD is chosen to be 250 mm (i.e., $S = 250$ mm in Eq. 2). Recall that the condition for a PPOA design requires $f$ to be infinite at a chosen nominal WD. In Fig. 3a, $f$ has been set at $10^4$ mm, which is virtually “infinite” relative to the dimensions of the imaging system. Additionally, since $S > F$, this system satisfies the PPOA condition. As a comparison, in Fig. 3b, $f$ has been set at 250 mm, which is the “infinite conjugate” setup described in section 2 of this paper, and therefore, does not satisfy the PPOA condition. The optical rays in the figures have been color coded (blue for Fig. 3a and green for Fig. 3b) for purposes of clarity. In Figs. 3a and 3b, the systems are at constant temperature, and the liquid lens focal lengths are unperturbed. In Figs. 4a and 4b, we have assumed that the temperature has changed in such a way that the liquid lens’s focal length has increased by 50% (i.e., $f = 1.5 \times 10^4$ mm in Fig. 4a, and $f = 1.5 \times 250$ mm in Fig. 4b). Note that the simulated image in Fig. 4a remains virtually unchanged, while the image in Fig. 4b has been blurred by thermal defocus. Comparison between the two simulated images in Figs. 4a and 4b illustrates that the PPOA configuration in Fig. 4a has reduced sensitivity to temperature variation.

4. Conclusion

For imaging systems that use LLMs as variable focus elements without active temperature feedback (such as the use of a thermistor), thermal defocus of the final image is minimized by setting up the FFL to image at finite conjugates, resulting in a partially athermalized system. In this white paper, we have referred to this configuration as partial passive optical athermalization (PPOA).
ABOUT VENTURE CORP. LTD.

Venture (SGX: V03) was founded in 1984 as a global electronics services provider. Today, it is a leading global provider of technology services, products and solutions with established capabilities spanning marketing research, design and development, product and process engineering, design for manufacturability, supply chain management, as well as product refurbishment and technical support across a range of high-mix, high-value and complex products.

The Group has built know-how and intellectual property with domain expertise in printing and imaging; advanced storage systems and devices; handheld interactive scanning and computing products; RF communications and network; test and measurement equipment; medical devices and life science equipment; retail store solution suite of products and industrial products and installations. Headquartered in Singapore, the Group comprises about 40 companies with global clusters of excellence in South-east Asia, North Asia, America and Europe and employs more than 12,000 people worldwide.

ABOUT ADVANCED PRODUCTS CORP. PTE. LTD. and “VEST”

Advanced Products Corp. (APC) is a wholly owned subsidiary of Venture Corp. Ltd. APC specializes in Embedded Systems Design & Development. Keeping a keen focus on its domain expertise, APC is uniquely positioned as an end-to-end total solution provider with VEST (Venture Embedded Solutions Technology) brand of products; additional products and technology beyond core systems to meet the demanding needs of various applications; as well as an extensive ecosystem of global services, support, and partners to address critical needs during each phase of the project, from design and development through to deployment and ongoing maintenance.

AUTHORS

Ronian Siew is an optics expert who spent much of his childhood constructing simple telescopes and spectrometers from scrap lenses. Today, his professional optical designs have included imaging and fluorescence detection systems for DNA analysis, and he is the author of a number of scientific peer-reviewed research papers. Ronian holds a MS in Optics and a degree in Physics from the University of Rochester.

Weehan Kuek is Director of R&D at Venture Corp. Ltd. and a technology enthusiast. He has held senior management positions across many disciplines, and he has directed successful technology projects that involve imaging and electro-mechanical systems for life science and analytical instruments. Weehan holds a BE in Mechanical Engineering from the National University of Singapore, and a MBA in Management of Technology from the Nanyang Business School, Nanyang Technological University, Singapore.

CONTACT

weehan.kuek@venture.com.sg | + 65 6484 8372
REFERENCES & NOTES

2. See, for example, http://www.varioptic.com/.
3. See, for example, http://www.optotune.com/.
4. For more information about embedded system controllers and SoMs, please visit http://apc-vest.com/.
5. See, for example, ref. 1, pp. 149 – 179.
7. We are using the term “focal length” synonymously with the more technical term known as “effective focal length”.
8. Minimizing thermal defocus by setting the liquid lens’s focal length to some specific value has also been suggested in Optotune’s datasheet for their EL-10-30C electrically tunable lens product series (see ref. 3). Although this concept may be regarded as a type of passive optical athermalization for liquid lens systems, it is actually quite distinct from those commonly discussed in available literature where liquid lenses with different thermal properties for their refractive index are carefully chosen such that thermal defocus effects from one lens essentially cancels the effect from another lens (e.g., see Refs. 9 – 11). In other systems, athermalization of liquid lenses is taken to mean the action of actively varying the liquid lens’s focal length in response to temperature changes as is discussed in the introduction of this white paper (see also Ref. 12).
13. We are borrowing the term “working distance” (WD) from machine vision, which refers to the distance between the object and the “front” of an imaging system. The front of an imaging system may be regarded as the front vertex of the first lens of the imaging system, or the front flange of the mechanical housing of the imaging system. In the present context, the “nominal WD” of an imaging system refers to the distance from the front surface of the imaging system to the position where the object ordinarily lies. Hence, the nominal WD is also the object distance for which the lens has been optimized during the process of lens design.